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# Life cycle assessment of buildings: A review

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ABSTRACT

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for various products (goods and services). Providing society with goods and services contribute to a wide range of environmental impacts. Environmental impacts include emissions into the environment and the consumption of resources as well as other inventions such as land use etc. In order to create an environmentally-conscious building, the environmental impacts of entire service life must be known. The aim of this study is to review various buildings at different places, whose LCA has been performed and to see that which phase of the life cycle of building and which type of building consumes more energy and have more greenhouse gas (GHG) emissions.

It has been observed that operational phase alone contributes more than 50% to GHG emissions and is highest energy consumer (80–85%) which is a matter of concern and cannot be ignored. Now there is a need for some alternative ways to design buildings for a sustainable future.



**Contents**



## 1. Introduction

As we know that today world is facing major environmental problems i.e. global warming, Ozone layer depletion, waste accumulation etc. Over the last few decades the research indicates that the global climate is changing rapidly [1] and also un-reveals the fact that this change will continue with time [2]. So there is an urgent need to mitigate these undesirable problems arising from our modern way of lifestyle to save our environment and our world.

Building plays an important role in consumption of energy all over the world. Building sector has a significant influence over the total natural resource consumption and on the emissions released. A building uses energy throughout its life i.e. from its construction to its demolition. The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, operation, rehabilitation and demolition in a building; whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations [3]. Massive construction activity is taking place globally to accommodate the migration of world's population to urban areas, a proportion that is expected to reach 60% by the year 2030 [4]. Such a boom in construction is considerable factor in order to save our resources from depletion.

Buildings can be categorised according to their usage i.e. residential and non-residential buildings. Residential buildings can further be divided into single-family house and multi-family house, and non-residential buildings are those which are used for commercial purposes i.e. school, university, office etc.

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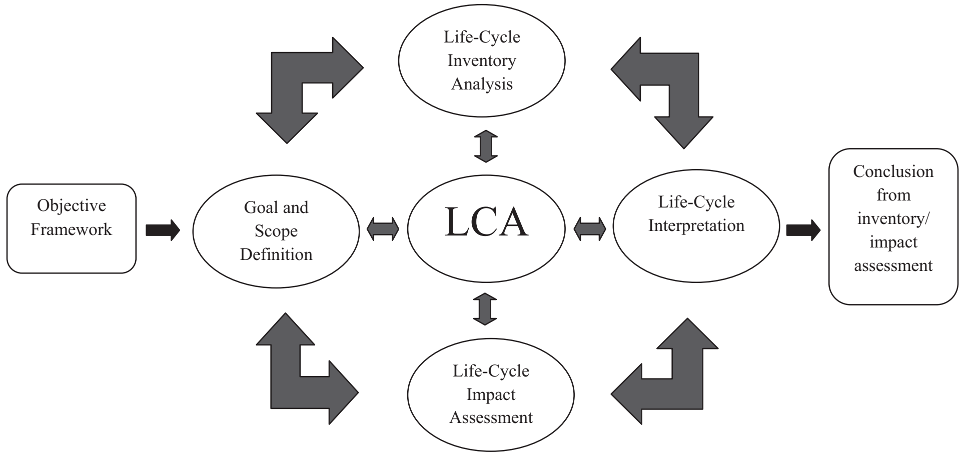



**Fig. 1.** Stages of life cycle assessment.

Life cycle assessment (LCA) is a tool used for the quantitative assessment of a material used, energy flows and environmental impacts of products. It is used to assess systematically the impact of each material and process. LCA is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product's life (i.e. cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal [5].

The concept of life cycle studies has developed over the years, in the years 1970s and 1980s, life cycle studies had focused on the quantification of energy and materials used and wastes released into the environment throughout the life cycle. LCA methodological framework comprises of four stages, i.e., goal and scope definition; life cycle inventory analysis; life cycle impact assessment; and life cycle interpretation and as shown in Fig. 1.

The goal and scope definition establishes the functional unit, system boundaries, and quality criteria for inventory data. The life cycle inventory analysis deals with the collection and synthesis of information on physical material and energy flows in various stages of the products lifecycle. In the life cycle impact assessment these environmental impacts of various flows of material and energy are assigned to different environmental impact categories, the characterisation factor is used to calculate the contribution of each of the constituents for different-different environmental indicators (GHG emissions, ozone layer depletion etc.). Finally the life cycle interpretation deals with the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment. It includes the identification of significant issues and the evaluation of results.

## 2. Energy in buildings

As real estate business is rapidly increasing and the need for quality internal environment and micro-surroundings has become key issues for both potential home buyers and estate developers. The data from a survey held at US states that approximately 4.6 million commercial building containing about 5.5 billion $m^2$ of floor area in the year 1995 uses annually 650 billion kWh of energy for space conditioning and ventilation [6]. Also according to California Energy Commission, California alone used over 8800 GWh of electricity in operating air-conditioning systems [7]. Over 40% of the total energy used in a building is consumed by heating, ventilation and air-conditioning (HVAC) systems [8]. A study in Europe states that building sector is responsible for about 40% of energy use and GHG emissions, out of which 2/3 times of energy use and GHG emissions are generated from residential buildings [9]. A residential building mainly uses energy for its heating in winter and cooling in summer. In Great Britain, half of the energy consumption and of the $CO_2$ emissions is due to this building sector only. In Argentina, the energy consumption by estate sector is 22% which comes in third place among the biggest energy consumers. The construction sector in India is experiencing unprecedented growth contributing 10% to India's GDP (Gross Domestic Product), and it is growing at a rate of 9.2% per annum as against the world average of 5.5%. Also there has been rapid increase in the consumption if electricity at a rate of about 13.2% during the last decade, in the residential and commercial building sector [10]. The domestic energy consumption, in terms of per capita net consumption, increased by 56% [11] which is an important issue of concern.

80–85% of the total energy use during the life cycle is used during the phase of occupancy, when building is used for the purpose for which it is constructed. It means that, the maximum energy consumption is during the use phase, when building is in use [12]. $CO_2$ is the main component which is released by the processes involved in building construction and its usage. Argentina was placed fourth in the ranking for the $CO_2$ emissions emitted by building sector alone in 1970 and after 20 years the ranking was upgraded to second position among the biggest contributors for GWP (Global Warming Potential). If we take a look on resource consumption during its construction, then the buildings consumes 40% of the stone, sand and gravel, 25% of wood, 40% of energy from fossil fuels; and 16% of water globally every year in the world [9]. As a study in Finland they identified that energy used in operations for heating and electricity, accounts for 80–90% of climate change and acidification impacts from buildings [13].

Energy is not only consumed but also a lot of waste is produced which is thrown in environment and produces harmful gases. These harmful gases contribute in GHG emissions. The influence of building sector over the environmental damage cannot be ignored. In general, influencing factors are: shape and orientation of building over its heating and cooling loads and the management of the building by its users on the strategies of energy savings and environmental control. The operation phase has the biggest share in contribution of these effects and the best time to reduce these effects is during the design and construction of a building.

## 3. LCA of buildings

According to Basket et al. [14], LCA is defined as comparative analysis tool which is used to evaluate environmental hazards and consumption of resources associated with the product, process or the activity over the entire life of the product [15,16]. In this paper various types of energy requirements in buildings used for

different purposes (residential, office or other type of buildings) has been discussed. These results are related to the function of a product, which allows comparisons between alternatives of the components used.

This tool is multi-disciplinary in the sense that also impact on the natural environment and even peoples relations to such impacts can be modelled [17]. LCA is also represented as tool for environmental product management. There is an international standard for LCA (i.e. ISO 14040 1997) that lists following applications: identification of improvement possibilities, decision making etc.

LCA may be categorised into following three types: Process LCA, Input–Output LCA and Hybrid LCA. Many LCAs utilizes either the process based [18,19] or input–output LCA techniques [20–24]. As energy issue is important for design and operation of a building hence some optimum methods are developed by Al-Homoud [25] which are very much user friendly.

### 3.1. LCA of residential buildings

Adalberth et al. [12] performed LCA on four multi-family buildings built in the year 1996 at Sweden. The functional unit was considered as usable floor area ($m^2$) and the lifetime of building was assumed to be 50 years. The main aim was to study different phases of life-cycle of all four buildings and to find out which phase has the highest environmental impact, and were there any differences in environmental impact due to the choice of building construction and framework. The environmental impact was evaluated with an LCA tool developed at Danish Building Research Institute [26]. In this study, the environmental impacts referred to GWP, AP (Acidification Potential), EP (Eutrophication Potential) and human toxicity. Different phases of a building considered were: manufacturing, transport, erection, occupation, renovation, demolition and removal phase. Value of energy consumption was calculated to be 6400 kWh/$m^2$.50yrs. The occupation phase alone accounts for about 70–90% of total environmental impact caused by a building, so it is important to choose such constructions and installations options which have less environmental impact during its occupation phase.

Arpke and Hutzler [27] used the LCA and LCC (life-cycle cost analysis) techniques to study the use of water in multi-occupant buildings. The selected locations for this study were Boulder, Colombia; Houghton, Michigan; Ames, Iowa and Newark, New Jersey located in US. In this analysis Building for Environment and Economic sustainability (BEES) [28] tool Version 3.0 has been used and it is applicable for both LCA and LCC. This tool was used to study a 25 year operational life cycle for plumbing fixtures and water-consuming appliances for four different multi-occupant buildings: an apartment, a college dormitory, a motel and an office building. The efficient fixtures and appliances should be used rather than conventional fixtures and appliances; and the use of natural gas rather than electricity for water heating should be done because $80,000 have been saved if natural gas is used to heat water as an alternate for electricity.

Norman et al. [29] compared high and low populated buildings for their energy use and GHG emissions. It illustrates that the choice of functional unit is highly relevant for full understanding of urban density effects and choose two functional units; living area (per $m^2$ basis) and number of lives in a house (per capita basis). Both the conditions were selected for Toronto (Canada). The EIO-LCA (Economic Input–Output based LCA) was used to estimate the environmental impacts of material manufacturing required for construction of infrastructure. EIO-LCA is a tool developed by researchers at Carnegie Mellon University [21]. For building operations nationally averaged public datasets were utilized and detailed location-specific data for the Greater Toronto area were used for public and private transportation. Energy use and GHG emission estimates for per person-kilometre for different transportation models were taken from previously submitted report by Kennedy [30]. This study shows that embodied energy and GHG emissions resulting from material production across the supply chain were approximately 1.5 times higher for low-density case study than the high-density case study on per capita basis; and the high-density development scenario becomes 1.25 times more energy and GHG emissions intensive than low-density if considered for unit living area basis. Also the EIO-LCA analysis performed in this study disclosed the fact that the most important construction materials contributing to embodied energy and GHGs for both density cases were brick, windows, drywall and structural concrete used in the buildings. These four materials in combined account for 60–70% of the total embodied energy and production related GHG impacts for both low and high-density case studies.

Guggemos and Horvath [31] compared environmental effects of steel and concrete framed buildings using LCA. Two five-storey buildings with floor area of 4400 $m^2$ were considered which were located in the Midwestern US and were expected to be used for 50 years. In this study two methods, process based LCA and EIO-LCA, were used to evaluate life-cycle environmental effects of each building through different phases: material manufacturing, construction, use, maintenance and demolition phase. The results showed that concrete structural-frame had more associate energy use and emissions due to longer installation process.

Blengini [32] performed LCA of building which was demolished in the year 2004 by controlled blasting. The adopted functional unit used in the current case-study was 1 $m^2$ net floor area, over a period of 1 year. This residential building was situated at Turin (Italy). In this study demolition phase and its recycling potential were studied. The life cycle impact assessment (LCIA) phase was initially focused on the characterisation and six energy and environmental indicators were considered, GER (Gross Energy Requirement), GWP, ODP (Ozone Depletion Potential), AP, EP and POCP (Photochemical Ozone Creation Potential). SimaPro 6.0 [33] and Boustead Model 5 [34] were used as supporting tools in order to implement the LCA model and carried out the results. The results demonstrated that building waste recycling is not only economically feasible and profitable but also sustainable from the energetic and environmental point of view.

### 3.2. LCA of commercial buildings

Junnila and Horvath [35] studied the significant environmental aspects of a new high-end office building with a life span of over 50 years. In this study functional unit is considered as 1 kW h/$m^2$/year and location of study was at Southern Finland (Northern Europe). The LCA performed here had three main phases – inventory analysis for quantifying emissions and wastes, impact assessment for evaluating the potential environmental impacts from the inventory of emissions and wastes, and interpretation for defining the most significant aspects. In this study life cycle of a building was divided into five main phases; building materials manufacturing, construction process, use of the building, maintenance, and demolition. The result shows that the most of the impacts are associated with electricity use and building materials manufacturing. Particularly, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing maintenance of steel, concrete and paint, and office waste management were identified as the most significant aspects. GHG emissions were estimated to be 48,000 ton $CO_{2eq}$/$m^2$.50yr.

Richman et al. [36] performed LCA for cold storage buildings in North America. They considered RSI value ($R$ = insulating value) as a functional unit. As energy loss is proportional to 1/$R$. The models

**Table 1**
Environmental impacts associated with different buildings.

| S. no. | Year | Specification of building | Place | Type | Life time (year) | Floor a rea ($m^2$) | Energy use ($MJ/m^2$.50yr) | GHG emissions ($CO_{2eq}/m^2$.50yr) | Acidification ($SO_{2eq}/m^2$.50yr) | Eutrophication ($/m^2$.50yr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1996 [12] | Malmo | Sweden | R | 50 | 700 | 23,040 | 1.30 ton | 0.0079 ton | 0.0042 $NO_{3eq}$ |
| 2 | 1996 [12] | Helsingborg | Sweden | R | 50 | 1,160 | 26,640 | 1.35 ton | 0.0081 ton | 0.0046 $NO_{3eq}$ |
| 3 | 1996 [12] | Vaxjo | Sweden | R | 50 | 1,190 | 33,120 | 1.51 ton | 0.0084 ton | 0.0049 $NO_{3eq}$ |
| 4 | 1996 [12] | Stockholm | Sweden | R | 50 | 1,520 | 2,590 | 1.40 ton | 0.0096 ton | 0.0044 $NO_{3eq}$ |
| 5 | 2006 [29] | Low-density building | Toronto, Canada | R | 50 | – | 53,400 | 5365 kg | – | – |
| 6 | 2006 [29] | High-density building | Toronto, Canada | R | 50 | – | 46,830 | 3885 kg | – | – |
| 7 | 2005 [31] | Steel framed | Midwestern US | R | 50 | 4,400 | 20,900 | – | – | – |
| 8 | 2005 [31] | Concrete framed | Midwestern US | R | 50 | 4,400 | 46,950 | – | – | – |
| 9 | 2004 [32] | Via Garrone building | Turin, Italy | R | – | 6,110 | 49,930 | 3340 kg | 920 mol | 175.1 kg $O_{2eq}$ |
| 10 | 2003 [35] | High-end | South. Finland, Europe | C | 50 | 15,600 | – | 48,000 ton | 130 kg | 16,000 kg $PO_{4eq}$ |
| 11 | 2003 [37] | Sam Wyly Hall, University of Michigan | Michigan, USA | C | 75 | 7,300 | – | 67,500 ton | 161.5 ton | 20 $PO_{4eq}$ |
| 12 | 2008 [46] | Office building | Thailand | C | 50 | 60,000 | – | 5,600,000 ton | 2200 ton | – |
| 13 | 2003 [9] | School building | Mendoza, Argentina | C | 50 | – | – | 34,000 μPE* | – | 3000 μPE* |

R: residential, C: commercial, μPE*: $10^{-6}$ person equivalents.

were simulated as if they were located in the cities of Tamp, Florida and Milwaukee, Wisconsin (US). This research basically examined the estimated average roof insulation requirement in modern cold storage buildings. Both environmental and economic aspects were considered. This study shows that there is a need to improve the level of insulation; depending upon the climatic conditions i.e. RSI-8.45 to RSI-9.86 insulation should be used in cold climates and RSI-9.86 to RSI-11.27 insulation should be used in warm climates.

Scheuer et al. [37] performed LCA on a 7300 $m^2$ six-storey building whose projected life was 75 years at SWH (Sam Wyly Hall). The building is located on the University of Michigan Campus, Ann Arbor, Michigan, US. LCA has been done in accordance with EPA (Environmental Protection Agency), SETAC (Society for Environmental Toxicity And Chemistry), and ISO standards for LCA [5,38–40]. Most of the data was taken from the DEAM™ database [41] and other material production data was taken from two databases by Swiss Agency for the Environment, Forests and Landscape [42,43], SimaPro software [44] and from Franklin Associates Reports [45]. Primary energy consumption, GWP, ODP, NP (nitrification potential), AP, and solid waste generation were the impact categories considered in the life cycle environmental impacts from SWH. Computer modelling was done in order to determine the primary energy consumption for heating, cooling, ventilation, lighting and water consumption. The primary energy intensity over the buildings, life cycle was calculated to be 316 $GJ/m^2$. HVAC and electricity alone accounts for 94.4% of life cycle primary energy consumption. An inventory analysis of three different phases: Material placement, Operations and Demolition phase was done. Results showed that the optimization of operations phase performance should be primary emphasis for design, as in all measures, operations phase alone accounted for more than 83% of total environmental burdens.

Kofoworola and Gheewala [46] operated an LCA for an office building in Thailand. The building used in this study is a 38 storey building in the central business district of Bangkok and its service life was estimated to be 50 years. The functional unit for this study was considered as 60,000 $m^2$ gross floor area of building. This study covered whole life cycle including material production, consumption, construction, occupation, maintenance, demolition and disposal. Inventory data was simulated in an LCA model and environmental impacts for each phase were computed. Main three impact categories considered were; GWP, AP and photo-oxidant potential. Two LCA methodologies were used in the study, i.e. a process-based LCA and the EIO-LCA [47–52]. The results shows that steel and concrete were the most significant materials, both in terms of quantities used and also for their associate environmental impacts at the manufacturing stage. Also the life cycle environmental impacts of commercial buildings are dominated by the operation stage, which accounts 52% of total global warming, 66% of total acidification and 71% of total photo-oxidant formation potential respectively.

Arena and Rosa [9] considered a school building and performed an LCA to compare different building technologies which have been applied in a rural school building for obtaining thermal comfort with minimum fossil energy consumption. This school building is situated in Lavalle, a small town in Northern Mendoza (Argentina). Life span of building was considered to be 50 years. A simplified LCA methodology was used and only construction and operational phases were considered. Environmental impacts which were considered in this study are; GWP, EP, ARP (Acid Rain Potential), PSP (Photo-Smog Potential), resource consumption and TP (Toxicity Potential). For all calculations regarding inventory, impact assessment and normalization phases the SBID (Society of British Interior Design) database was used [53]. The annual energy savings and global energy savings (for 50 years) were calculated and showed that the annual energy savings during use phase were 5307.5 MJ/year, and global energy savings for 50 years life span were 265374.5 MJ/year. This study showed that almost all the environmental aspects investigated were improved when conservative technologies were implemented.

## 4. Discussions

The results of various case studies have been shown in Table 1. This table shows the effect of buildings on various environmental categories, i.e., GHG emissions, energy use, AP and EP. Commercial buildings were found to have more impact on environment as compared to the residential buildings. Also the energy consumption of commercial building is high than that of residential buildings. The key factors for energy use in buildings are transportation, building material production, construction, during the pre-use life cycle phase; electricity use, HVAC, manufacturing and maintenance, water use, waste generation, natural resource consumption during use (operational) phase; building demolition,

recycling, during end-of-life phase. For overall life cycle of a building, construction phase impacts are relatively smaller (0.4–11%) [31].

During the operational phase the maximum energy is consumed as well as the emissions are also maximum (80–85% of total energy consumption and emissions) [12].

## 5. Conclusion

Buildings play major role in energy consumption of the total available energy. The estate sector, whether residential or commercial, the energy is consumed at high rate and hence contributes a lot in consumption of fossil fuels and emission of various hazardous gases which leads to global harms like ODP, greenhouse effect and acidification etc.

There are many different alternatives for building construction if they could be implemented during construction phase of a building. Although all the life cycle phases were found to have significant environmental aspects but operational phase has the highest percentage (80–85%) of energy consumption in the life cycle of a building. Similar results have also been accounted for different countries. If construction of a building is done with keeping the effects of operational phase in mind than a performance based building can be constructed, which will not only save energy but also our economy.

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